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Real-time testing of the on-site warning algorithm in southern California and its performance during the July 29 2008 M_w5.4 Chino Hills earthquake

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[1] The real-time performance of the τ_c-P_d on-site early warning algorithm currently is being tested within the California Integrated Seismic Network (CISN). Since January 2007, the algorithm has detected 58 local earthquakes in southern California and Baja with moment magnitudes of $3.0 \le M_w \le 5.4$. Combined with newly derived station corrections the algorithm allowed for rapid determination of moment magnitudes and Modified Mercalli Intensity (MMI) with uncertainties of ±0.5 and ±0.7 units, respectively. The majority of reporting delays ranged from 9 to 16 s. The largest event, the July 29 2008 M_w5.4 Chino Hills earthquake, triggered a total of 60 CISN stations in epicentral distances of up to 250 km. Magnitude predictions at these stations ranged from M_w4.4 to M_w6.5 with a median of M_w5.6. The closest station would have provided up to 6 s warning at Los Angeles City Hall, located 50 km to the west-northwest of Chino Hills.
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1. Introduction

[2] The purpose of earthquake early warning (EEW) is to provide real-time information about earthquakes to distant sites before the seismic S or surface waves arrive. Because warning times usually are extremely short, EEW systems must recognize the severity of expected ground motions within seconds after the P-wave arrival at the EEW sensors. If warnings can be issued in a timely manner, suitable actions for damage mitigation can be initiated and executed [e.g., *Goltz*, 2002].

[3] Currently, the performance of the τ_c-P_d on-site warning algorithm [*Kanamori*, 2005; *Wu and Kanamori*, 2005a, 2005b; *Wu et al.*, 2007; *Wu and Kanamori*, 2008a, 2008b] is being real-time tested within the California Integrated Seismic Network (CISN) [*Hauksson et al.*, 2006]. The algorithm is based on single sensor observations using two parameters: period parameter τ_c and high-pass filtered displacement amplitude P_d. Both parameters are determined from the vertical components of velocity and/or displacement data, $\dot{u}$ and u, using the first $t_0 = 3$ s of P-waveforms. The period parameter τ_c, computed by

$$\tau_c = 2\pi / \sqrt{\left[\int_0^{t_0} \dot{u}^2(t)dt\right] / \left[\int_0^{t_0} u^2(t)dt\right]},$$

approximately represents the P-wave pulse width [*Wu et al.*, 2008b]. Previous studies have determined empirical relationships between τ_c and the moment magnitudes M_w, and between P_d and the peak ground velocities (PGV) at the sites of observation [*Kanamori*, 2005; *Wu and Kanamori*, 2005a, 2005b]. *Wu et al.* [2007] established corresponding relationships for earthquakes in southern California using seismic off-line data. Observed and estimated values of PGV can be transformed into Modified Mercalli Intensity (MMI) scale using empirical relationships developed by *Wald et al.* [1999].

[4] For the real-time testing, we have implemented the τ_c -P_d algorithm in an UNIX environment, using existing software components developed by the California Institute of Technology (Caltech), the U.S. Geological Survey (USGS), and UC Berkeley, that are built on software systems developed for the CISN and the Advanced National Seismic System (ANSS). The processing steps are as follows [*Solanki et al.*, 2007]: (1) retrieve velocity data from the CISN; (2) set the baseline to 0 by using average values continuously determined from the real-time data streams in intervals of 60 s, and apply gain correction; (3) convert velocity to displacement data by recursive integration; apply high-pass Butterworth filter (>0.075 Hz); (4) calculate τ_c and P_d from the initial 3 s of waveform data; (5) keep only triggers with τ_c-P_d combinations that are characteristic of a local earthquake [*Böse et al.*, 2009]: for a local earthquake with period τ_c in a rupture-to-site distance r, $r_{\min} \le r \le r_{\max}$, we expect $P_{d,\min} \le P_d \le P_{d,\max}$. *Böse et al.* [2009] determined displacement amplitudes $P_{d,\min}$ and $P_{d,\max}$ from empirical attenuation relations for earthquakes in southern California with $r_{\min} = 1$ km and $r_{\max} = 100$ km. To avoid false alerts, we currently require the triggering of at least 3 stations before an earthquake is processed.

[5] To improve the accuracy of M_w and PGV estimates, we refined in this study the τ_c-M_w and P_d-PGV relations by *Wu et al.* [2007] with new station corrections. We determined these factors from the median of residuals from (1) 431 off-line estimates of M_w during 27 earthquakes ($4.0 \le M_w \le 7.3$) [*Wu et al.*, 2007], and from (2) 257 real-time estimates of M_w during 58 earthquakes ($3.0 \le M_w \le 5.4$) as analyzed in this paper. Correction factors were determined and applied in this study only for stations for which at least 2 records were available.

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Table 1. Performance of the On-Site Warning Algorithm at Caltech During 9 Local Earthquakes (M_w > 4.5) in Southern California and Baja[a]

Origin Time (PST)	Latitude and Longitude (deg)	M_w	Number of Reports	Time of First Report	First Reporting Station	Estimated M_w at First Reporting Station	Median and Scattering in M_w Over All Reports
2008-7-29 11:42:15 Chino Hills	33.95 −117.76	5.4	60	11:42:25 (10 s after O.T.)	CI.PSR.[b] (Δ = 16 km)	5.6	5.6 4.4–6.5
2008-2-8 23:12:04	32.36 −115.28	5.1	5	23:12:30 (26 s after O.T.)	CI.DRE[c] (Δ = 52 km)	5.4	5.4 5.1–5.9
2008-2-11 10:29:30	32.33 −115.26	5.1	2	10:29:57 (27 s after O.T.)	CI.DRE[c] (Δ = 56 km)	5.3	5.0 4.8–5.3
2008-2-19 14:41:29	32.43 −115.31	5.0	5	14:41:52 (23 s after O.T.)	CI.DRE[c] (Δ = 43 km)	4.8	5.0 4.7–6.0
2008-2-11 20:32:39	32.45 −115.32	5.0	6	20:33:02 (23 s after O.T.)	CI.DRE[c] (Δ = 41 km)	4.7	5.0 4.4–5.4
2008-2-19 17:28:55	32.43 −115.31	4.8	4	17:29:18 (23 s after O.T.)	CI.DRE[c] (Δ = 44 km)	4.0	4.9 4.0–5.5
2008-2-22 11:31:18	32.42 −115.29	4.8	1	11:31:41 (23 s after O.T.)	CI.DRE[c] (Δ = 45 km)	4.6	4.6
2007-9-2 10:29:14	33.73 −117.45	4.7	27	10:29:34 (20 s after O.T.)	CI.CHN[d] (Δ = 35 km)	3.9	4.6 3.2–5.6
2007-8-9 00:58:49	34.30 −118.62	4.6	26	00:59:03 (14 s after O.T.)	CI.RIN[d] (Δ = 13 km)	4.6	4.6 3.9–5.9

[a]Magnitude estimates are station corrected. O.T. is origin time, Δ epicentral distance.
[b]Q330; direct ethernet radio link to Caltech.
[c]Q4120; frame relay.
[d]Q4120; Virtual Private Network (VPN) over microwave.

[6] Based on the performance between January 2007 and September 2008, we want to analyze in this paper (1) the real-time applicability of the τ_c-P_d on-site warning algorithm for earthquakes in southern California, and (2) the suitability of the current CISN instrumentation and telemetry for issuing EEW. Of course, small and moderate-sized earthquakes (M_w < 6.0) as analyzed in this paper usually will not cause damage and therefore do not require EEW. To gain experience more quickly and to have working algorithms when large earthquakes occur, we use the more frequent small events for testing and calibrating of EEW algorithms and systems [*Böse et al.*, 2009].

2. Data

[7] The τ_c-P_d on-site warning algorithm at Caltech currently processes the waveform data from about 160 broadband stations of the California Integrated (CI) and Anza (AZ) networks deployed in southern California [*Böse et al.*, 2009], including stations with 80 and 100 samples per second. Since January 2007, the τ_c-P_d algorithm has processed 58 local earthquakes in southern California and Baja with $3.0 \leq M_w \leq 5.4$ with a total of 257 triggers. The July 29th, 2008 M_w5.4 Chino Hills mainshock in the eastern Los Angeles Basin (33.95°N, −117.76°W, 14.7 km depth) was the largest earthquake to occur in the greater Los Angeles metropolitan area since the M_w6.7 Northridge earthquake in 1994. The event was widely felt across southern California, but caused only minor damage [*Hauksson et al.*, 2008]. The Chino Hills earthquake sequence produced 97 estimates of M_w and PGV values by the τ_c-P_d algorithm: 60 during the M_w5.4 mainshock (Table 1) and between 8 and 15 during the three largest aftershocks (M_w2.8, M_w3.8, and M_w3.6).

[8] The current EEW system at Caltech uses broadband observations only. To avoid the clipping of wave amplitudes during large magnitude earthquakes and earthquakes at close distances, we recently started to integrate strong motion sensors in addition. To test the performance of the τ_c-P_d algorithm for this type of data, we also processed in this study, in an off-line mode, acceleration records of the Chino Hills mainshock from 11 CISN stations at epicentral distances of $\Delta \leq 30$ km.

3. Results

[9] Both M_w and PGV values of the 58 local earthquakes were estimated automatically by our software from the observed τ_c and P_d values using the relations proposed by *Wu et al.* [2007]. The real-time estimated parameters correlate well with the corresponding values reported by CISN (Figures 1a and 1c). However, the scatter is often quite large, sometimes with outliers of as much as two magnitude units. The median values, taken for each earthquake over all available M_w estimates, usually show a slight overestimation of M_w by 0.3 units. The uncertainties in the predictions of magnitude (Figure 1a) and the logarithmic values of PGV (Figure 1c) are ±0.6 and ±0.3 units, respectively. The latter is equivalent to an uncertainty of ±0.75 MMI intensity units [*Wald et al.*, 1999].

[10] The newly derived station corrections lead to significant improvement of the predictions, but some outliers still remain (Figures 1b and 1d); the majority of them are associated with events with small magnitudes (M_w < 4.5) and large epicentral distances (Δ > 150 km), i.e. are caused by poor signal-to-noise ratios. The station corrections reduce the errors in magnitude and intensity estimates to ±0.5 and ±0.7 units, respectively (Figures 1b and 1d). In general, the M_w and PGV values estimated from the off-line processed strong motion data agree well with the real-time processed broadband observations of the Chino Hills earth-

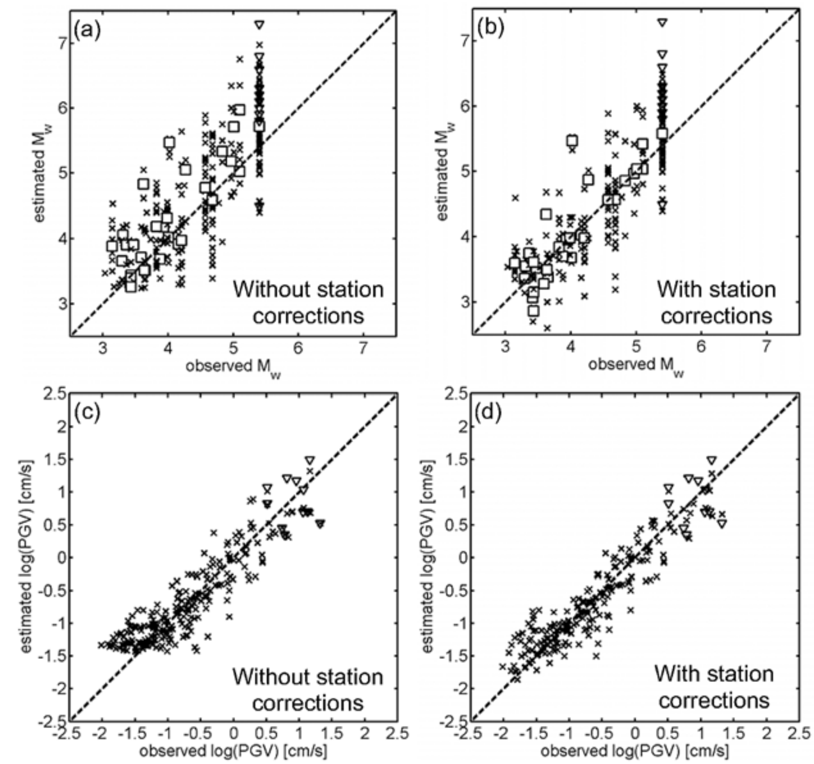

Figure 1. Estimated vs. observed source and ground motion parameters of 58 local earthquakes ($3.0 \leq M_w \leq 5.4$) in southern California and Baja: (a and b) moment magnitudes M_w and (c and d) peak ground velocities (PGV). Estimates in Figures 1b and 1d include correction factors, which are applied to stations with observations during at least two earthquakes. Crosses show real-time processed data, triangles off-line processed strong motion data of the July 29 2008 M_w5.4 Chino Hills earthquake. The median M_w values in Figures 1a and 1b, taken over the magnitude estimates of each earthquake, are shown by squares. Values along the dashed lines show a perfect correlation.

quake (triangles in Figures 1a–1d), but show more scatter, possibly due to poor signal-to-noise ratios. Note that the strong motion data in Figures 1a–1d are not station corrected.

[11] The largest outlier in Figures 1a and 1b is observed for a M_w4.0 earthquake which occurred on March 30, 2007 at six kilometers east of Coso Junction, an area known for the frequent occurrence of earthquake swarms: the magnitude of this event was overestimated by 1.5 units. *Böse et al.* [2009] suspected that this overestimation might have been caused by a small foreshock which occurred 48 s before the mainshock resulting in a high background noise level at the majority of close EEW stations before and during the arrival of the seismic P phase from the mainshock. Although such foreshocks are relatively rare, the real-time identification of such events will pose a major challenge in the future developments of EEW systems [*Böse et al.*, 2009].

[12] The real-time performance of the τ_c-P_d on-site warning algorithm for all analyzed earthquakes with $M_w >$ 4.5 is summarized in Table 1. The errors in the station corrected estimates of M_w at the first reporting station reach from 0.0 to 0.8 units. Six of the events occurred within an earthquake swarm near the Cerro Prieto Geothermal field at the U.S./Mexican border, which started ~20 miles southeast of Calexico with a M_w5.1 earthquake on February 8, 2008 (http://www.scsn.org/2008bajaaddendum.html). Note that the first reporting station CI.DRE is located at approximately 40 to 55 km north, i.e. relatively far away from the epicenters of the large events in the swarm. The first magnitude and PGV estimates thus were not available until 23 s after origin time (O.T.).

[13] The first magnitude prediction of the M_w5.4 Chino Hills mainshock was available 10 s after O.T. (M_w5.6 at station CI.PSR). Subsequent (independent) estimates based on data from other stations ranged from M_w4.4 to M_w6.5 with a median value of M_w5.6 (Table 1). The MMI intensities determined from PGV [*Wald et al.*, 1999] were slightly underestimated by 0.2 ± 0.8 units. The largest prediction errors occurred in the western part of the Los Angeles basin where seismic wave amplitudes were strongly amplified due to basin effects (Figures 2a and 2b). Because the current database is insufficient for the determination of correction terms for many of the stations shown in Figure 2b, the PGV estimates in the map are not station corrected.

[14] Neglecting the telemetry and processing delays of the current system, each single estimate in Figure 2b could have been made available within 3 s after the P-wave arrival (This is the time required by the τ_c-P_d algorithm.). The entire map in Figure 2b was available in less than 1 minute after O.T.. For comparison the first automatically generated CISN ShakeMap [*Wald et al.*, 1999] of the Chino Hills earthquake was released about 12 minutes after O.T. [*Hauksson et al.*, 2008].

[15] To illustrate the effect of EEW delays in more detail, we have drawn in Figure 2 circles centered at the epicenter of the M_w5.4 Chino Hills earthquake. These circles show

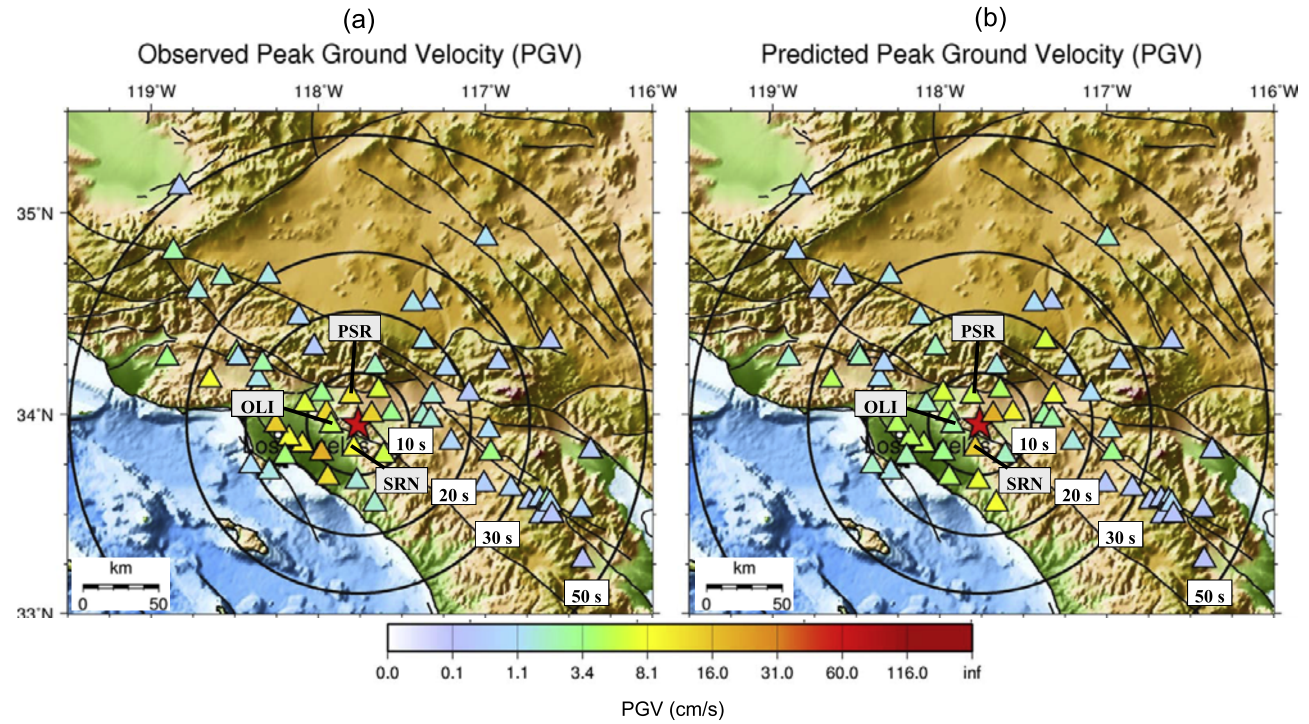

Figure 2. Distribution of (a) observed and (b) predicted values of peak ground velocity (PGV) at 60 CISN stations triggered by the EEW software during the July 29 2008 M_w5.4 Chino Hills earthquake. Neglecting telemetry and processing delays, each single estimate in Figure 2b could have been made available within 3 s after P-wave arrival. Circles show S-wave arrivals at 10 s, 20 s, 30 s and 50 s after origin time (O.T.). The current system provided a first estimate of M_w and PGV 10 s after O.T., i.e. in an operational EEW system, only sites outside of the smallest circle could have obtained a warning using the current CISN stations and equipment.

the predicted locations of the S-wave arrivals at 10 s, 20 s, 30 s and 50 s after O.T., assuming a constant shear wave velocity of 3.2 km/s. Depending on the time, at which a warning or estimate is delivered, only sites outside of the corresponding circle can obtain a warning before the S wave arrives. This delay depends on (a) the P-wave arrival time at the reporting EEW sensor, which is controlled by the station density, and (b) the so-called *warning delay* between P-wave arrival and the reporting of parameters and/or warnings. The warning delays include delays caused by station equipment (in particular by the type of datalogger), by telemetry of waveform data to the central processing facility at Caltech, 3 s waveform data required by the τ_c-P_d algorithm, and processing delays. In an operational system, additional delays will be caused by the transmission of warnings to users.

[16] The current CISN configuration provided a first estimate 10 s after O.T. of the Chino Hills mainshock (Table 1). In an operational EEW system, only sites outside of the smallest circle in Figure 2 with a radius of 30 km could have obtained a warning. As an example, at Los Angeles City Hall, located 50 km to the west-northwest of Chino Hills, the current system would have provided up to 6 s warning before S-wave arrival. For comparison the first M_L estimate (M_L5.6) by CISN was automatically released ~80 s after O.T., an up-dated estimate (M_L5.8) around 60 s later. The automatic moment tensor and M_w estimate (M_w5.4) were available ~10 min after O.T. [*Hauksson et al.*, 2008].

[17] From January to September 2008, the testing system at Caltech recorded around 50,000 triggers, which were mostly not caused by local earthquakes and not processed by the EEW algorithm. Fortuitously, these triggers provide data for comprehensive statistics of warning delays. The majority of warning delays range from 9 to 16 s (Figure 3). The older generation Refteks in the Anza network use both microwave and internet based telemetry. While older generations of CISN dataloggers (Q4120 and Q730) transmit ~3 s of demultiplexed miniSEED waveform packets, the new Q330 dataloggers transmit data packets of 1 s multiplexed waveform data. We have developed the capability of capturing and analyzing these 1 s packets and therewith were able to reduce the warning delays by several seconds.

4. Discussion and Conclusions

[18] Between January 2007 and September 2008, 58 local earthquakes with $3.0 \le M_w \le 5.4$ were real-time processed by the EEW software at Caltech, including the July 29 2008 M_w5.4 Chino Hills earthquake as the largest event. The performance during these events demonstrates the real-time applicability of the τ_c-P_d algorithm.

[19] A scatter in the real-time predicted values of M_w for both on- and off-line processed earthquakes (Figure 1a) is unavoidable, because τ_c is affected by many factors, including source (radiation patterns, directivity, and stress drop), propagation and site effects. Poor signal-to-noise ratios pose an additional problem for small magnitude events ($M_w < 4.5$) and events at large epicentral distances ($\Delta > 150$ km). The scatter can be reduced by the application of station correc-

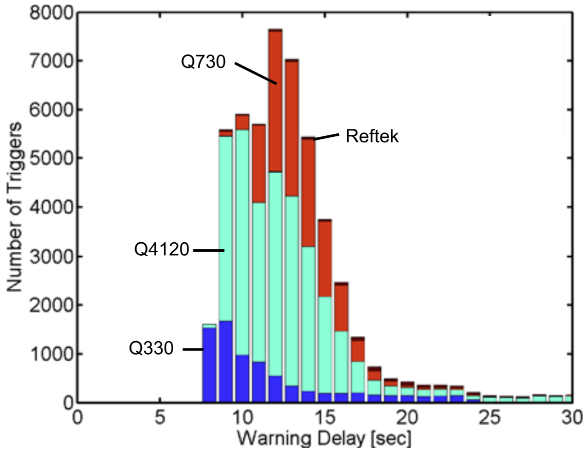

Figure 3. Warning delays between P-wave arrivals at the CISN stations and the reporting of M_w and PGV values at Caltech. The delays include times required for the processing and communication of the waveform data, i.e. delays caused by station equipment (in particular types of dataloggers, see legend), the telemetry, 3 s required by the τ_c-P_d algorithm, and the centralized waveform processing at Caltech. The histogram shows triggers obtained between Jan. and Sept. 2008.

tions (Figures 1b and 1d). The current database includes station corrections only at a small subset of CISN stations, but we plan to up-date the station corrections with data from future earthquakes.

[20] At present, we are working on the implementation of the remote processing sites for the BK, NP, NC, and PG networks operated by UC Berkeley and USGS Menlo Park in northern California. These processing sites will analyze available local waveform data and provide τ_c-P_d values as well as M_w and PGV estimates, i.e. more data for algorithm testing will become available. Based on this data, further tests of the τ_c-M_w and P_d-PGV relations for earthquakes in California will be undertaken.

[21] The future inclusion of strong motion channels in the EEW system at Caltech will help avoid clipping of wave amplitudes during strong and close earthquakes and will help increase the required station density for EEW. As shown in this paper, M_w and PGV estimates obtained from strong motion records with $\Delta \leq 30$ km are in good agreement with broadband observations.

[22] The current test system at Caltech uses a 3 s long time window to determine the EEW parameters τ_c and P_d. Previous studies have shown that it should be possible to recognize from this time window if $M_w \leq 6.5$ or $M_w > 6.5$ [*Kanamori*, 2005]. We chose the 3 s length as a compromise between recognizing a large magnitude earthquake and issuing estimates and warnings as soon as possible. In the future, additional research needs to be undertaken to determine the optimum length of the window, including both moderate and large magnitude earthquakes [*Böse et al.*, 2009].

[23] The performance results of the EEW software at Caltech reveal technological limitations of the current CISN instrumentation and telemetry for issuing early warnings. The majority of warning delays based on the CISN infrastructure range from 9 to 16 s (Figure 3). The speed of delivery mainly depends on the type of datalogger and telemetry path. To eliminate delays caused by the telemetry of waveform data, we recently started to implement the τ_c-P_d algorithm software on SLATE Field Processors. SLATE receives data from a Q330 datalogger on-site, computes τ_c and P_d, and transmits M_w and PGV estimates to Caltech as a short notification message. Warning delays are expected to decrease significantly compared to the current centralized processing of waveform data at Caltech. In the future, such station processors can also transmit warnings to local users directly.

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